

Small signal stability analysis of dish-Stirling solar thermal based autonomous hybrid energy system



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ABSTRACT

Present work presents small signal stability analysis of an autonomous hybrid energy system with dish-Stirling solar thermal systems (DSTS) in integration with diesel engine generators (DEG), fuel cells (FC), battery energy storage system (BESS), and aqua electrolyzer (AE). The performance of Genetic algorithm (GA) optimized integral (I), proportional plus integral (PI), and proportional-integral-derivative (PID) controllers in containing the frequency deviation in the proposed system has been investigated. The dynamic performance of all three controllers, so optimized, is compared with manually tuned I controller. Simulation results revealed that the performance of the GA optimized PID controller is found to be the best amongst all three controllers. Further, sensitivity analysis is carried out to access the robustness of the controllers.

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Introduction

Anticipating the energy crisis due to continued depletion of the world's most valuable fossil energy resources and environmental hazards to be faced in the coming decades, concentrating solar thermal technology has been recognized as a promising candidate to provide critical solutions to global energy problems within a relatively short time frame without or with minimum carbon emission. Among all the renewable technologies that exist for large-scale power production today and for the next few decades, solar thermal technology is perhaps the best option to make significant contributions of clean energy because of its use of relatively conventional technology and ease of scale-up [1]. To date, major solar thermal technologies include solar power tower, solar parabolic trough, solar dish-engine, linear fresnel systems and zero to low concentration low temperature solar thermal systems. Out of these solar thermal technologies dish-Stirling solar thermal system is the most suitable one for stand-alone applications, because of modular design and the highest record for solar-to electric energy conversion efficiency among all solar thermal technologies. However, the detail study on the dynamic performance of controllers of an autonomous hybrid energy system with dish-Stirling solar thermal system is not yet reported.

Actually dish Stirling solar thermal technology is one of the oldest solar technologies. There are number of past and current demonstration projects, mostly in Europe, Japan, Australia and in USA [2,3]. All dish Stirling system deployments are reported in [4,5]. During last 20 years, eight different dish-Stirling systems ranging from 2 to 50 kW have been constructed by companies in the United States, Germany, Japan and Russia [6]. A plant with installed capacity 1.5 MW is in operation in Peoria, AZ, and plants with rated capacity of several hundred megawatts are in the planning stages [7]. In August 2005, Southern California Edison entered into an agreement with Stirling Engine Systems (SES) for purchasing power for 20-years using parabolic dish units of capacity between 500 and 850 MW (producing 1182–2010 GW h per year). Same year in September, SES publicized a contract with San Diego Gas & Electric to provide between 300 and 900 MW of solar power using the dish technology. Among operational solar dish systems around the world, 3 kW plant by Infinia Corp. and 10 kW by Schlaigh-Bergermann und Partner up to 150 kW by Stirling Energy Systems or Wizard Power Pty [4] are worth mentioning.

There are few more large projects currently under planning and construction that are worth highlighting because of their significant power size. These projects use Stirling Energy Systems technology and are located in the USA with an installed capacity of 750 and 850 MW and in India using Infinia Corp. Technology with a capacity of 9–10 MW [8]. Other than these, two dish Stirling systems, which are developed and expected to be in operation in commercial scale in 2010: the Euro Dish from Schlaigh-Bergermann at Eskom in South Africa and Partner (SBP) and the

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Nomenclature

Δf	system frequency deviation.	T_{BESS}	time constant of battery energy storage system.
K_{sys}	frequency characteristic constant of hybrid power system.	$G_{\text{AE}(s)}$	transfer function of aqua electrolyzers.
$G_{\text{SYS}(s)}$	transfer function of hybrid power system.	P_{AE}	Aqua electrolyzers power.
P_{DEG}	output power of diesel generators.	K_{AE}	gain of the aqua electrolyzer.
$G_{\text{DEG}(s)}$	transfer function of diesel generator.	T_{AE}	time constant of the aqua electrolyzer.
K_{DEG}	gain of diesel generator.	P_{S}	total power generation to the system.
T_{DEG}	time constant of diesel generator.	P_{L}	average power absorbed by loads.
P_{FC}	output power of fuel-cell generators.	ΔPe	error in power supply and demand.
K_{FC}	gain of fuel cell.	M	inertia constant of the hybrid power system.
T_{FC}	time constant of fuel cell.	D	damping constant of the hybrid power system.
$G_{\text{FC}(s)}$	transfer function of fuel-cell generators.	<i>Abbreviations or subscripts</i>	
P_{DSTS}	output power of dish-Stirling solar thermal system.	GA	genetic algorithm
$G_{\text{DSTS}(s)}$	transfer function of dish-Stirling solar thermal system.	AE	aqua-electrolyzer
T_{DSTS}	time constant of dish-Stirling solar thermal system.	DEG	diesel-engine generator
K_{DSTS}	gain of the dish-Stirling solar thermal system.	FC	fuel cells
P_{BESS}	power of battery energy storage system.	BESS	battery energy storage system
$G_{\text{BESS}(s)}$	transfer function of battery energy storage system.	PS	power system
K_{BESS}	gain of battery energy storage system.	DSTS	dish-Stirling solar thermal system

“SunCatcher Dish Stirling system” developed by Stirling Energy Systems (SES) in Spain [2].

Significant development in this technology is the construction of large scale solar dish Stirling systems within the framework of Solar One and Solar Two projects of company Stirling Energy System (SES), which was launched on 2005 [2]. The two projects, overall, will include 64,000 dishes, generating 1750 MW, which will provide electricity for approximately 1,100,000 homes.

Increasing penetration of dish-Stirling solar thermal power into the utility grid demands for simulation studies to assess the dish-Stirling system's impact on steady state and transient behavior of the utility grid, a topic that has not attracted much attention of the researchers till date. Because of its unpredictable nature and dependency on weather and climatic changes, the variations of solar thermal energy may not match with the time distribution of load demand. Fortunately, the problems caused by the variable nature of this resource can be partially or wholly overcome by hybridization with fossil fuel based backup systems. A fossil based backup system allows the compensation of solar input fluctuations and permits night-time operation. And the integration of energy storage systems into the solar plant allows an increase in annual solar operating hours as well as compensates short time fluctuations in the solar energy input [9,10]. In this paper, a dish-Stirling solar thermal diesel autonomous hybrid energy system has been proposed. Diesel provides a cushion against variation in dish-Stirling solar thermal power in an isolated hybrid energy system, thereby increasing the reliability of the system.

Like wind energy, dish Stirling electric power is also characterized by intermittent nature and use of a non-conventional, asynchronous generator [7]. Because of the intermittency of solar energy in dish Stirling systems, both voltage and frequency of utility grid fluctuates. Present work considers frequency control of dish-Stirling solar thermal based autonomous hybrid energy system.

Studies on wind-diesel-energy storage based hybrid energy systems have been carried out in the past. Lee and Wang [11] are the first to propose and discuss the basic concept of effective utilization of renewable energy sources in an isolated hybrid system. Their proposed autonomous hybrid system consists of wind turbine generators, photo voltaic system, fuel cells, diesel engine generator and energy storage system in different combination. However, they have not investigated thoroughly into different

control schemes and their performance including effective coordination among various subsystems. In time-domain analysis of case 1, they have considered that during $0 \leq t < 50$ s aqua electrolyzer would absorb a fraction of energy generated by wind generators even when total power generated by three wind turbine generators is less than 0.3 p.u. and diesel generator would supply 0.9 p.u. to mitigate the difference in generation and load. While electrolyzer absorbs a fraction of wind energy during low wind penetration and supplies the hydrogen so produced to fuel cell, diesel generator is used to supply rest of the load demand to mitigate power mismatch. The power control and management concept is unwise from economical point of view. Further, their simulation results revealed that the dynamics of hydrogen generation by absorption of energy, and supply of hydrogen to the fuel cell occurred simultaneously.

Another study on autonomous hybrid system comprising of wind turbine generators, diesel generators, fuel cells, and aqua electrolyzer, conducted by Senjyu et al. [12]. Prime objective is to mitigate effect of wind power fluctuations by using electrolyzer, and control of system frequency by altering the output power generation of subsystems by employing controllers. Aqua electrolyzers absorb the rapidly fluctuating output power from wind turbine generators and generate hydrogen. Generated hydrogen by an aqua electrolyzer is used as fuel for fuel-cell generators. The proportional plus integral (PI) controllers were employed to regulate the output powers from distributed generation system to achieve power balance condition due to sudden variations in generation and load. The proposed system improves the efficiency of the system. However, the gain values of PI controller are chosen by trial and error method which does not ensure the optimal performance of the controller.

There are several tuning methods in literature e.g., Ziegler-Nichols Ultimate-cycle tuning, Cohen-Coon's, Astrom and Hagglund and many other traditional techniques. Although new methods are proposed for tuning the controllers, their usage is limited due to complexities arising at the time of implementation [13]. The method described in Ziegler and Nichols is conventional one. The controller gains once tuned for a given operating point are only suitable for limited operating point changes. Therefore, the use of the conventional PI controller does not meet the requirements of the robust performance [14]. Moreover, when the number of parameters to be optimized is large, conventional technique

for optimization is certainly not preferred one. As because power system contains many nonlinearities; tuning of controller becomes a complex problem. Therefore, to date, the main focuses of research in control engineering has been devoted to the use of simultaneous automatic tuning of controller parameters [15]. In this paper GA has been used to optimize the controller parameters simultaneously.

In view of the above, it is felt worthy to investigate the effectiveness of different control strategies and appropriate coordination among various subsystems in a dish-Stirling solar thermal based autonomous hybrid energy system to meet power balance condition. Proposed hybrid system consists of dish-Stirling solar thermal system, diesel generator, battery energy storage device, aqua-electrolyzer and fuel cells. To resolve the challenges related to frequency control it is proposed to ensure power balance through automatic generation control associated with energy storage devices. The controller parameters are proposed to be optimized using GA, a heuristic search technique. The proposed control strategy will be capable of supplying or absorbing active power rapidly to mitigate oscillations so as to maintain the system frequency within acceptable range in an autonomous hybrid energy system.

This paper is organized as follows: section 'Proposed hybrid system' presents the overview and mathematical modeling of the proposed hybrid system; section 'Genetic algorithm' illustrates GA. Simulation results and their analysis have been carried out in sections 'Case studies, simulation results and analysis' and section 'Conclusion' presents the conclusions.

Proposed hybrid system

Conceptual dish-Stirling solar thermal diesel autonomous hybrid energy system and the functional block diagram are shown in Figs. 1 and 2 respectively. Table 1 shows the parameters of the proposed hybrid system. The conceived autonomous hybrid energy system consists of dish-Stirling solar thermal systems (200 kW), diesel generator (150 kW), fuel cell (50 kW), Aqua electrolyzer (50 kW), battery energy storage device (150 kW h) and load (250 kW). The power supplied to the load is the sum of output

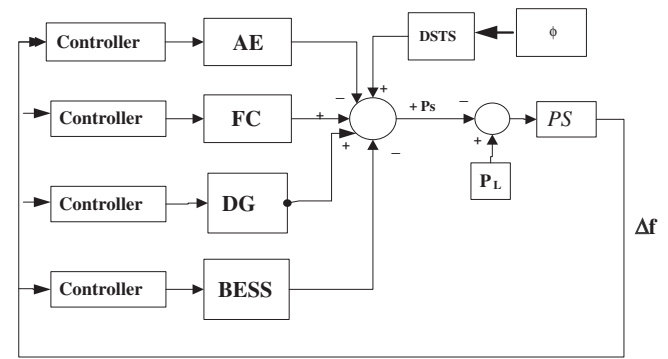


Fig. 2. Block diagram of dish-Stirling solar thermal based autonomous hybrid energy system.

Table 1

Parameters of the proposed hybrid system.

Gains	Time constants (sec)
$K_{DSTS} = 1.0$	$T_{DSTS} = 5$
$K_{AE} = -1/500$	$T_{AE} = 0.5$
$K_{DEG} = 1/300$	$T_{DEG} = 2$
$K_{FC} = 1/100$	$T_{FC} = 4$
$K_{BESS} = -1/300$	$T_{BESS} = 0.1$

powers from diesel generator, dish-Stirling solar thermal system, fuel cell and battery energy storage system. The aqua electrolyzer is used to absorb the fluctuations of solar thermal energy by producing the hydrogen gas which can be used as input to fuel cell generator. Overview of each system components and their mathematical models with first order transfer functions are presented in this section.

Dish-Stirling dish-Stirling solar thermal system

Fig. 3 shows the conceptual dish-Stirling system with labeled components. The system mainly consists of parabolic dish, receiver

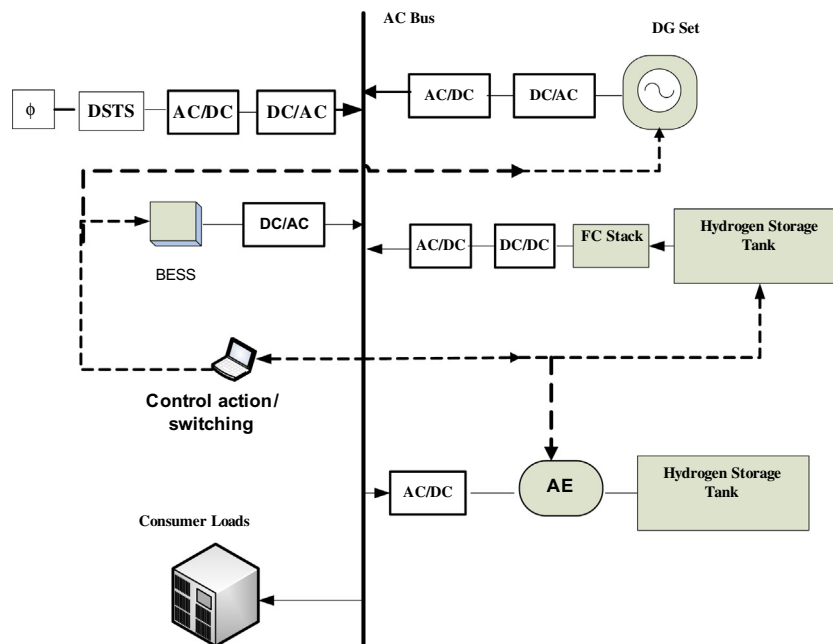


Fig. 1. Concept of dish-Stirling solar thermal based autonomous hybrid energy system.

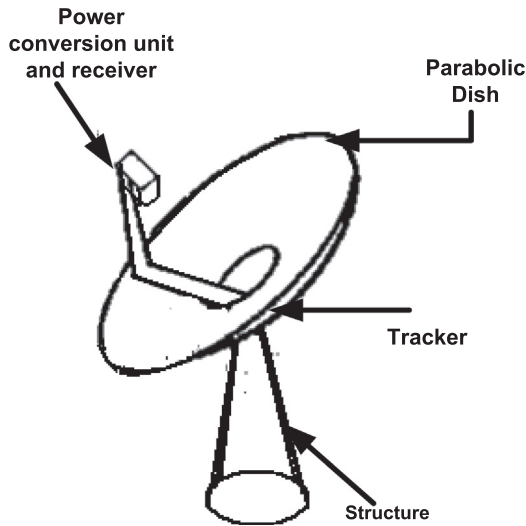


Fig. 3. Dish-Stirling system with labeled components.

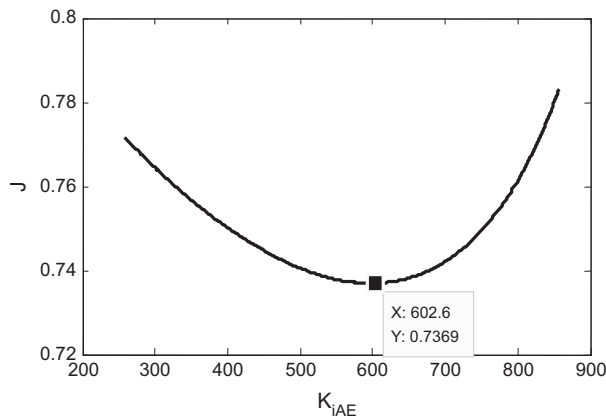


Fig. 4a. Plot of objective function value versus gain of the I controller, employed with AE.

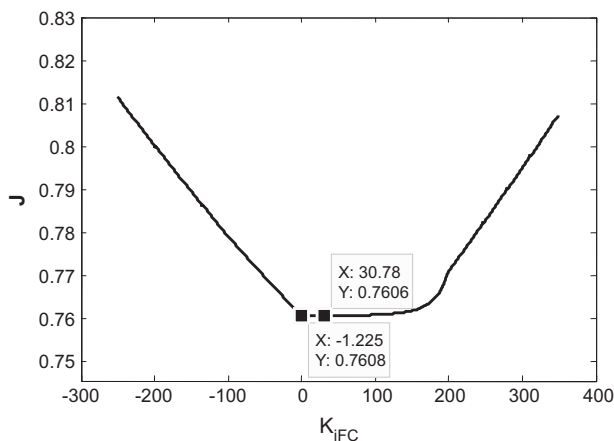


Fig. 4b. Plot of objective function value versus gain of the integral controller, employed with FC.

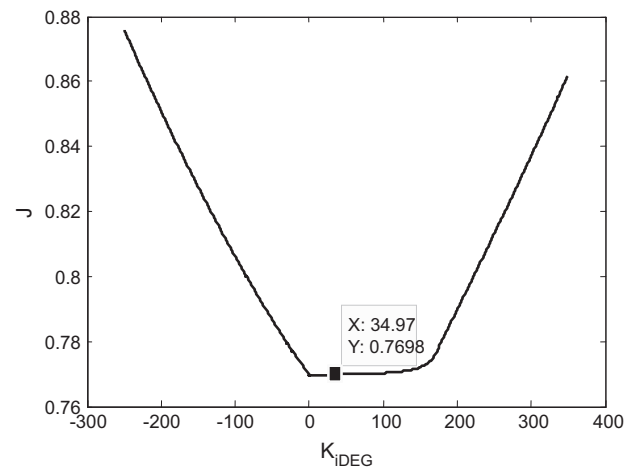


Fig. 4c. Plot of objective function value versus gain of the integral controller, employed with DEG.

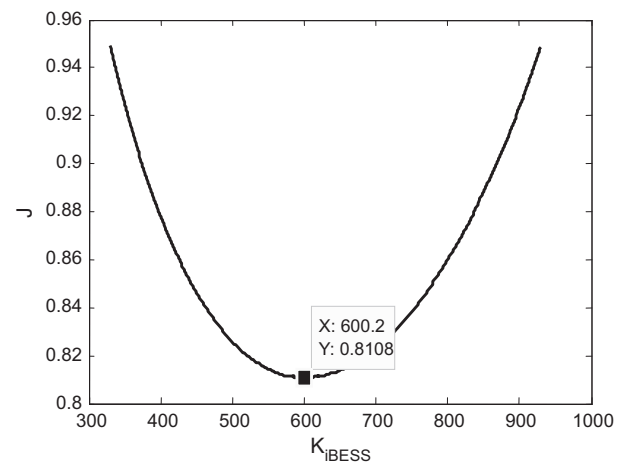


Fig. 4d. Plot of objective function value versus gain of the integral controller, employed with BESS.

energy to heat the working fluid. The commonly used working fluids are water, hydrogen, or helium gas. A Stirling engine is usually used as a prime mover in parabolic dish system, which is typically coupled to a squirrel cage induction generator. Thermal energy of the working fluids is transferred as input energy for the Stirling engine. The engine converts externally supplied thermal energy into mechanical torque using repeated heating/cooling of working fluids in a closed loop, which then drives the generator to produce electricity. In case of water being the working fluid the superheated steam is produced in receiver at about 750 °C [16]. The principal advantages of Stirling engine is its use of an external heat source and high efficiency. External heating makes the engine easily adaptable to any sources of thermal energy as long as the energy is properly transferred into the working gas. Owing to this advantage, Stirling engine has drawn much interest from various renewable energy technologies. In addition, it has emission free and relatively low noise operation as compared to the internal combustion engine [17].

Typical range of irradiance for dish-Stirling operation lies between 200 and 1000 W/m² and the system cannot generally operate at irradiance levels lower than 200 W/m² [7]. Dish Stirling has demonstrated net solar-to-electric conversion efficiency as high as 31.25% [2], which is the highest among all the solar thermal technologies available to date. Kongtragool and Wongwises [18]

and tracking device. The parabolic reflector concentrates and focuses the sunlight on to the receiver. The concentration ratio of dish concentrator can reach 1500–3000. The receiver, which is installed at the focus of the parabolic dish, collects the thermal

reported highest per unit capacity of 50 kW solar-powered Stirling engine for electricity production using a single membrane dish concentrator and hydrogen as a working gas [18]. For large-scale electricity generation, a number of dish Stirling system can be clustered to produce 1–10 MW. With the world's record for highest solar-to grid energy conversion efficiency among all solar thermal technologies, it is likely that significant entry in stand-alone energy market will occur soon.

The current status of dish-Stirling systems that are being developed for commercial markets, system specifications, system performance, economics, capital cost, operating and maintenance costs are discussed in [19].

The challenges involved in ensuring power quality of dish Stirling integrated systems are technically similar to that of wind integrated energy systems. Rising penetration of dish-Stirling solar power within the utility grid demands simulation studies to assess the impact of dish-Stirling systems on steady state and transient behavior of the utility grid and to access potential problem and find out possible solutions. This topic has ignored in literature to date.

Stirling engine torque is proportional to the pressure of the working gas. Engine torque therefore, decreases with decrease in the working gas pressure. Stirling engine shaft speed depends on the amount of available torque from the engine being balanced by the counter torque of the induction generator (squirrel cage induction machine). Typically, the engine runs at 2200 rpm and drives a standard induction generator through a gear reduction drive at 1800 rpm [19]. The technology employs a pressure control system that can supply or remove working gas from the Stirling engine's external gas storage tanks.

In actual systems, dish Stirling engine is a high-order model and have nonlinearity. However, present work considers only the low-frequency domain. Therefore, in this work, the transfer function represented by first-order lag has been considered [8].

$$G_{DSTS}(s) = \frac{K_{DSTS}}{1 + sT_{DSTS}} \quad (1)$$

where K_{DSTS} and T_{DSTS} are the gain and time constant of the dish-Stirling system. $K_{DSS} = 1$ and $T_{DSS} = 5$ s. K_{DSTS} and T_{DSTS} are chosen from the simulation results in [7] and [8]. Kongtragool and Wongwises [18] proposed the approximate equation of power output of Stirling engine:

$$P = 0.015P_m V_p f \quad (2)$$

where P is the engine power output in Watts, p_m the mean cycle pressure in bar, f the cycle frequency in Hz, and V_p is displacement of power piston in cm^3 .

Diesel generator

Diesel engine produces the torque, driving the synchronous machine generating the electrical power output. Because of sudden changes in load demands by the consumers, it is important that the diesel prime mover has a fast dynamic response and good capabilities of disturbance rejection.

A diesel generator is a nonlinear system because of presence of a nonlinear, time-varying dead time between the injection and production of the mechanical torque. Engine model gives the description of the fuel consumption rate as a function of speed and mechanical power at the output of the engine. The transfer function describes relation between fuel consumption and engine mechanical power [20]. In this paper, diesel generator is modeled by a simple first order transfer function proposed in [11,21]

$$G_{DEG}(s) = \frac{K_{DEG}}{T_{DEG}s + 1} \quad (3)$$

Aqua electrolyzer

Aqua electrolyzers are used to absorb the rapidly fluctuating output power from dish-Stirling solar thermal systems and generate hydrogen. The generated hydrogen is stored in the hydrogen tank and used as fuel for fuel. The decomposition of water into hydrogen and oxygen can be achieved by passing the electric current between the two electrodes separated by aqueous electrolyte. The transfer function model of aqua electrolyzer can be expressed by [11]

$$G_{AE}(s) = \frac{K_{AE}}{T_{AES}s + 1} \quad (4)$$

Since a typical AE consists of several power converters, time constant of the AE is very small [11].

Fuel cell

Fuel cell generates power through the electrochemical reaction between hydrogen and oxygen. Fuel cell offer alternatives to conventional generators, such as diesel generators, that would allow power to be produced without noise or on-site pollutants. A typical fuel cell produces a small dc voltage that is converted into ac using dc–ac converter. To create enough voltage, the cells are layered and combined in series and parallel circuits to form a fuel-cell stack. Fuel-cell developers claim a higher efficiency than traditional combustion technologies. The only drawback, as fuel-cell proponents concede, is that hydrogen is still more expensive than other energy sources such as coal, oil and natural gas. Fuel cell generator is a higher order model and has non linearity. For low frequency domain analysis it is represented by a first order lag transfer function model as proposed in [11]

$$G_{FC}(s) = \frac{K_{FC}}{T_{FCS}s + 1} \quad (5)$$

Load model

To examine effects of variation of loading in power demand a variable load model is developed as shown in Fig. 8f. The random fluctuation is generated from white noise block, using low-pass and high-pass filters respectively [21]. This model has been included in case-study 3.

Battery energy storage system

The short time power fluctuation from dish-Stirling solar thermal system causes large problems for power systems operation. A possible solution is storage of energy. Due to very good technical characteristics (large energy density, fast access time) the battery energy storage system has been an effective energy storage technology to store large amount of energy [21]. They can supply the system with a large amount of the power in a short time, or large amount of energy for a longer period. The Battery Energy Storage System (BESS) consists of a battery bank and a power converter [22] that interfaces the battery bank to the autonomous utility grid. A higher power capacity can be achieved by connecting more modules. The transfer function model of battery energy storage system expressed by first order is as in [11]

$$G_{BESS}(s) = \frac{K_{BESS}}{T_{BESS}s + 1} \quad (6)$$

2.7. Power and frequency deviations

In order to provide good quality of supply to the consumers it is very important maintain the scheduled frequency under varying

Table 2
Parameters of GA.

GA parameter	Value
Maximum number of generation	200
Population size	50
Crossover probability	0.6
Mutation probability	0.05

demand and supply conditions. Frequency can be maintained at desired level by managing the active power balance between the generation and demand. A hybrid system with dish-Stirling solar thermal system as one of the generating unit requires special control strategies because of highly fluctuating nature of solar radiation. The strategies to be adopted to alleviate mismatch between generation and demand can be by controlling the fuel to diesel electric power-generating unit, and/or other generating units. Generally conventional PI or PID controllers are used for this purpose. Recent trend is use of GA optimized controller.

In this paper, power control strategy is obtained by the difference between the power demand reference P_L and total power generation P_S .

$$\Delta P_e = P_S - P_L \quad (7)$$

Because system frequency changes with net power variation, the system frequency variation Δf is calculated by [11]

$$\Delta f = \frac{\Delta P_e}{K_{sys}} + D \quad (8)$$

Since an inherent time delay exists between system frequency variation and power deviation, the transfer function for system frequency variation to per unit power deviation can be expressed by [11]

$$G_{sys}(s) = \frac{\Delta f}{\Delta P_e} = \frac{1}{K_{sys}(1 + sT_{sys})} = \frac{1}{M_s + D} \quad (9)$$

Genetic algorithm

The GA is an optimization technique inspired by the principles of Darwinian Theory of natural selection, a biological process in which stronger individual is likely to be the winners in a competing environment. It was first proposed by Holland in 1975 [23]. Since then it has been useful in solving a wide variety of optimization problem including problems in which the objective function is discontinuous, non-differentiable, stochastic, highly nonlinear, or highly complex problems [24]. Fig. 5 presents an illustrative flowchart of the GA algorithm implementation.

The algorithm begins by creating a random initial population. Then it creates a sequence of new generations. At each step, the

Table 3
Simulation conditions for each case.

Case	Subsystems	Simulation time (s)	Operating conditions
Case 1	DSTS, AE, FC, DEG, BESS & Load	120	$P_{DSTS} = 0.4$ p.u. at $0 < t < 80$ s $= 0.6$ p.u. at $t > 80$ s $P_L = 0.5$ p.u.
Case 2			$P_{DSTS} = 0.4$ p.u. at $0 < t < 80$ s $= 0.6$ p.u. at $t > 80$ s $P_L = 0.5$ p.u. at $t = 40$ s $= 0.6$ p.u. at $t < 40$ s $= 0.4$ p.u. at $t > 80$ s
Case 3			Randomly variable DSTS & Load (Fig. 8a)

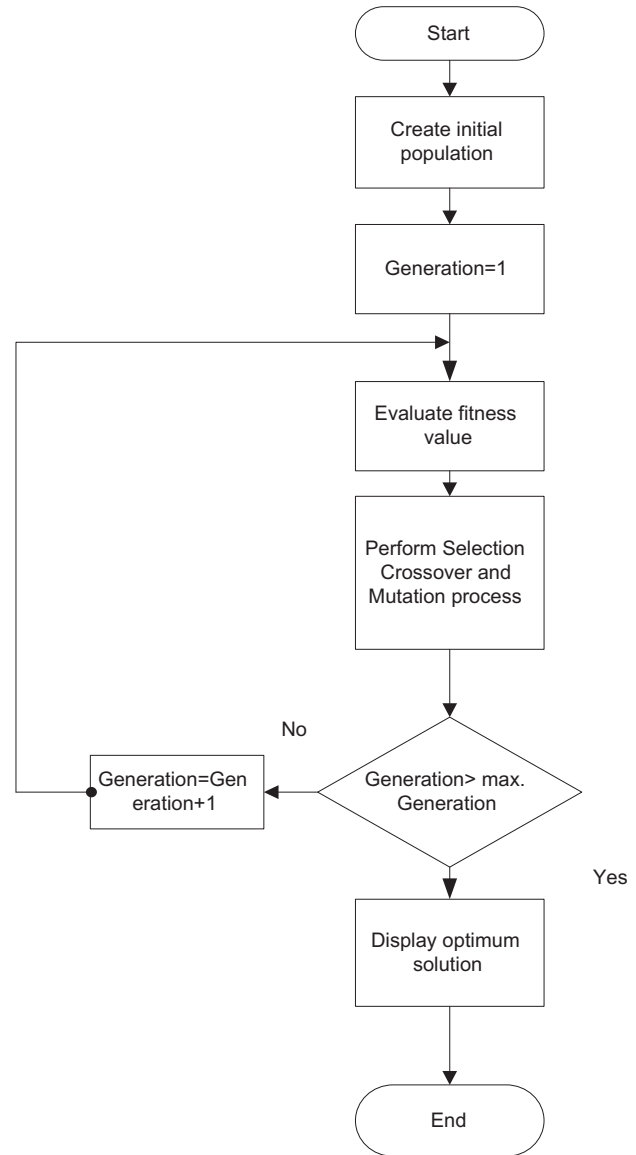


Fig. 5. Flowchart of Genetic algorithm.

algorithm uses the individuals in the current generation to create the next generation. In order to create new generation, the algorithm computes the fitness value each member of the current population. Selects parents based on their fitness. Highly fit individuals have a higher probability of being selected and producing children for next generation. The selected individuals are then improved through application of three basic operators i.e., Selection, Crossover and Mutation. The algorithm is repeated for many generations and stops when one of the stopping criteria is met.

The steps involves in optimizing the PID controllers using GA as illustrated in [21], are summarized as follows:

Step1: Create a population of initial solution of parameters (K_p , K_i , K_d). Each parameter in the problem is called as a gene. A Chromosome consists of the genes and thus each chromosome represents a solution to the problem.

Step 2: Evaluation of objective function. In the present problem, Integral Square of the frequency deviation is to be minimized. For each chromosome, the MATLAB model is simulated and performance index, J is computed.

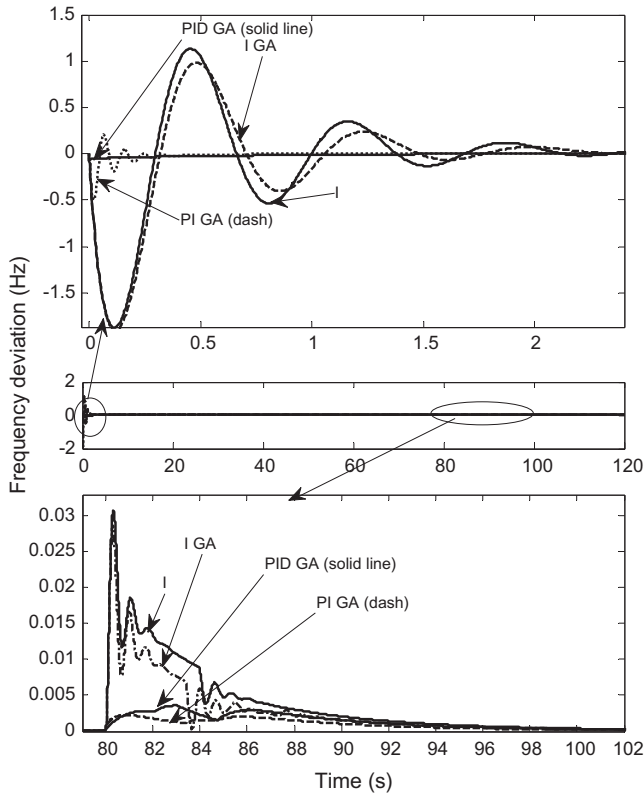


Fig. 6a. Frequency deviation.

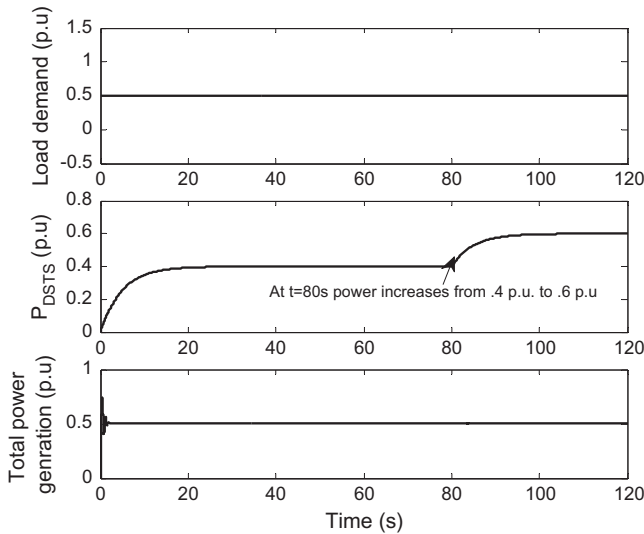


Fig. 6b. Load demand, power output from DSTS and total power generation.

Step 3: Evaluation of fitness function. The degree of fitness of a solution is qualified by assigning a value to it. This is done by defining a proper fitness function for the problem. Since GA is used here for minimization, the fitness function is objective function is the fitness function.

Step 4: Generation of offspring: Offspring is a new chromosome obtained through the steps of selection, crossover and mutation. After fitness of each chromosome is computed, parent solutions are selected for reproduction. It emulates the survival of the fittest mechanism in nature. Following the selection of parent population, crossover and mutation are performed to

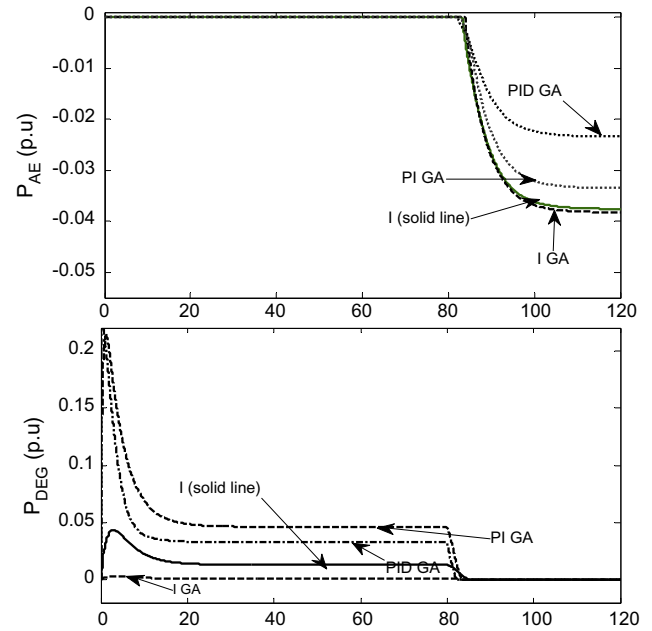


Fig. 6c. Input power to AE, output power of DEG.

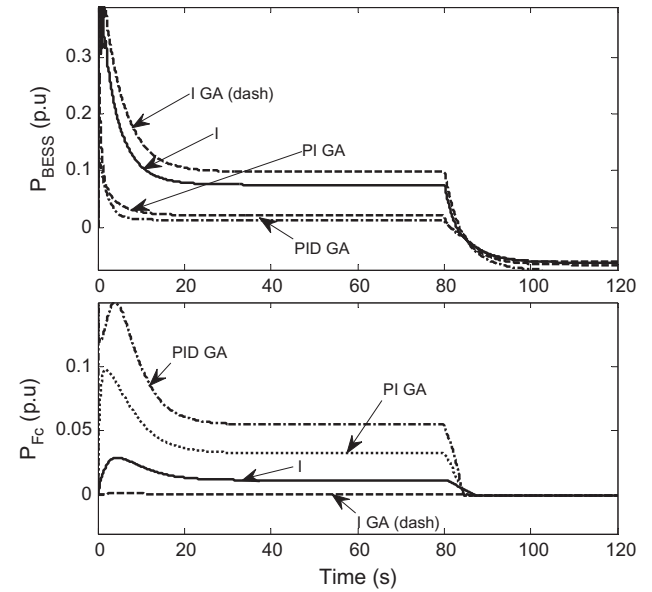


Fig. 6d. Output power of BESS, and FC.

Table 4
Gains of I controllers.

Gains Case	GA optimized values Case1	Conventionally optimized value Case1
K_{IAE}	622.4712	602.6
K_{IFC}	1.2336	30.78
K_{IDG}	2.0016	34.97
K_{IBESS}	602.8008	600.2

generate offspring population. The crossover and mutation are performed based on the probability of crossover and mutation. Step5: Replace the current population with the new population. Step6: Terminate the program if termination criterion is reached; else go to step 2

Table 5
Gains of PI and PID controllers.

Gains Case	GA optimized values		
	Case1	Case2	Case3
<i>PI controller</i>			
K _{pAE}	253.8	874.021	667.6
K _{iAE}	1088.2	742.043	796.5
K _{pFC}	987.7	999.2	993.9
K _{iFC}	664.7	137.5	644.2
K _{pDG}	1347.8	1399.4	1399.8
K _{iDG}	945.3	397.3	122.7
K _{pBESS}	1491.9	1491.8	1528.8
K _{iBESS}	1294.2	1125.6	838.7
<i>PID</i>			
K _{pAE}	331.2	330.4	917.6
K _{iAE}	281.1	1032	87.7
K _{dAE}	156.7	184.2	77.1
K _{pFC}	999.09	913.6	910.3
K _{iFC}	801.0	123.104	938.5
K _{dFC}	972.8	713.9	953.2
K _{pDG}	1381.4	1390.9	1379.4
K _{iDG}	477.6	715.3	700.6
K _{dDG}	852.9	879.8	869.6
K _{pBESS}	9004.4	877	7171.6
K _{iBESS}	552.6	1425	136.7
K _{dBESS}	11.3	990.7	333.2

In PID controller design methods, the most common objective functions are integrated absolute error (IAE), the integrated of time weight square error (ITSE) and integrated of squared error (ISE) etc. These three integral performance criteria have their own advantages and disadvantages. In this paper, integral of the square of frequency deviation is chosen as the objective function.

$$J = \int_0^t (\Delta f)^2 dt \quad (10)$$

The objective of the problem is to

Minimize J

Subject to

$$K_p^{\min} \leq K_p \leq K_p^{\max} \quad (11)$$

$$K_i^{\min} \leq K_i \leq K_i^{\max} \quad (12)$$

$$K_d^{\min} \leq K_d \leq K_d^{\max} \quad (13)$$

So, Fitness_{*i*} = 1/(1 + J) for i^{th} chromosome. (14)

The minimization of the objective function is implemented to determine the optimal parameters of PID controllers. The gains of PI controllers are optimized in the similar manner.

Genetic algorithm (GA) is a computationally simple and powerful algorithm and has been employed successfully in the field of sociology, science and technology [25–27]. The objectives of the present work are to investigate into the comparative performance of GA with manual trial and error method in optimizing the controller parameters for new hybrid energy system. GA parameters are presented in Table 2.

Table 6
Maximum frequency deviations (Δf in Hz) of dish-Stirling solar thermal based hybrid energy system for various operating conditions.

Case	Case1		Case2		Case3	
	Undershoot	Overshoot	Undershoot	Overshoot	Undershoot	Overshoot
I conventional	−1.9107	1.0379	–	–	–	–
I GA	−1.9108	.9824	–	–	–	–
PI GA	−.4987	.004	−.5071	.2049	−.0572	.0223
PID GA	−.0612	.0056	−.0307	.0163	−.0027	.0000895

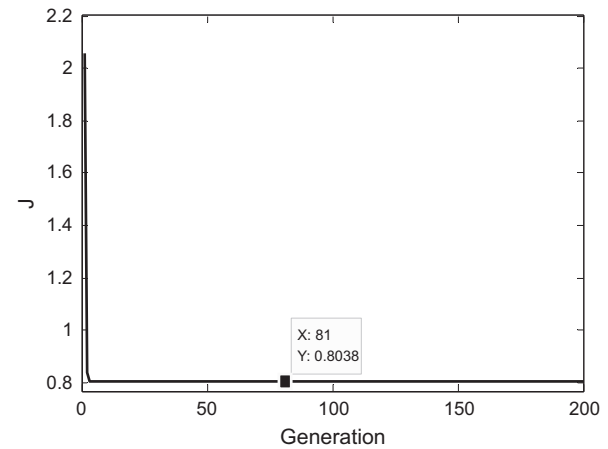


Fig. 6e. Plot of objective function value versus generation for the model with GA optimized I Controller.

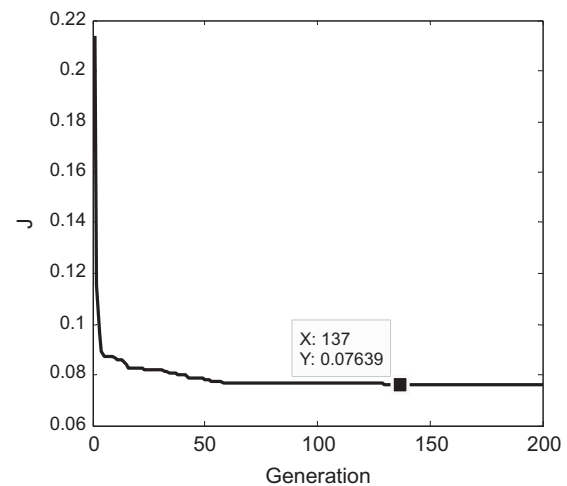


Fig. 6f. Plot of objective function value versus generation for the model with GA optimized PI controller.

Case studies, simulation results and analysis

The sensitivity of frequency is determined by the system inertia. A large interconnected system has considerable system inertia; therefore, frequency excursion in the presence of renewable energy is small. However, in case of an isolated hybrid system, the presence of renewable energy poses considerable effects on the system inertia, and frequency controllers need to take care of long rates of change of system frequency and variations of operating point changes. Isolated hybrid energy system proposed in this present work, employs controllers to take care of frequency variations. Assumed generating subsystems employ suitable power converters for exchanging energy with the studied ac system. BESS is

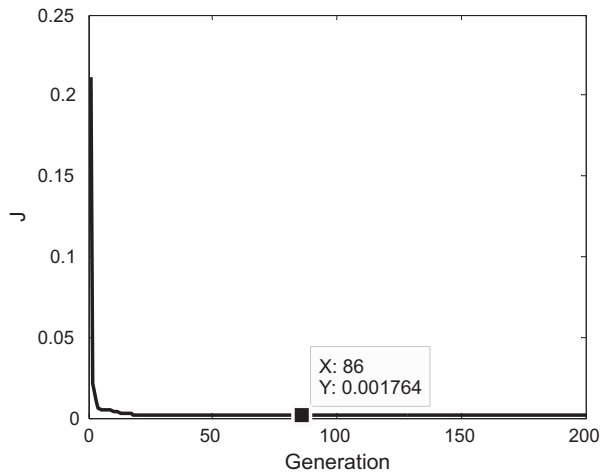


Fig. 6g. Plot of objective function value versus generation for the model with GA optimized PID controller.

assumed to have enough capacity to store surplus energy generated by the generating subsystems. When the power from DSTS decreases or load demand increases, the BESS can supply enough energy to the load within a very short time. As the dynamics of BESS is faster than FC [28], it switches on first. The DEG automatically starts up to deliver power to the system when the total power generated by the DSTS, FC, and BESS is not sufficient.

Program evaluation and simulations are carried out in Matlab7.9 for obtaining the dynamic responses. The objective of the present work is to compare the competence of the GA based method in finding the optimal gains with the conventional trial and error one. The tuned parameters for GA are presented in Table 2. The manual trial and error based optimization is an indirect optimization approach, in which a sequential optimization method is used. In this method one parameter is optimized at a time using ISE criterion keeping the other parameters fixed at the same time. Then this operation is repeated for every other parameter to complete one iteration of optimization. Optimization of the controller gains by the aforesaid manual method of optimization is time consuming. In this work, the investigations of manually tuned controllers is, however, confined to I controllers only. Following three case-studies as mentioned in Table 3, for the same hybrid energy system under different operating points are considered. It is to be noted that the simulation has been carried out considering p.u. power ratings of all the subsystems.

The responses of the system under various operating points and disturbance conditions are presented with optimum gain settings of conventional I controller and GA based I, PI, PID controllers, respectively.

Time-domain analysis: case1

The power generation in this case can be expressed by

$$P_S = P_{\text{DEG}} + P_{\text{DSTP}} + P_{\text{FC}} - P_{\text{AE}} \pm P_{\text{BESS}} \quad (15)$$

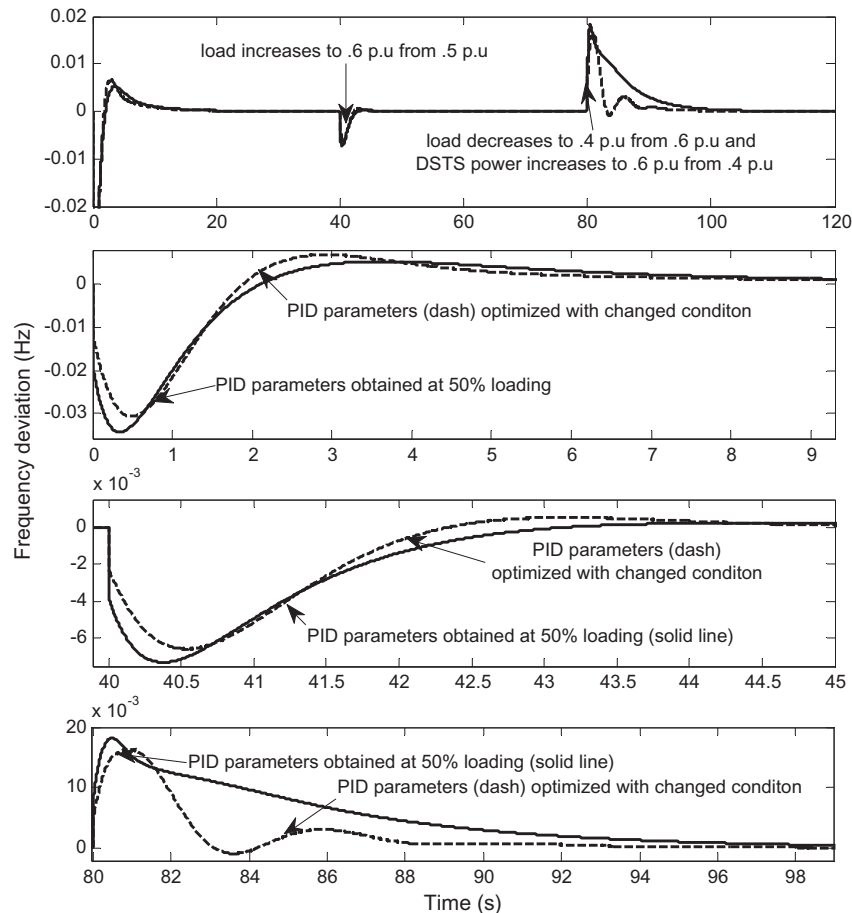


Fig. 7a. Frequency deviation in case of GA optimized PID controller.

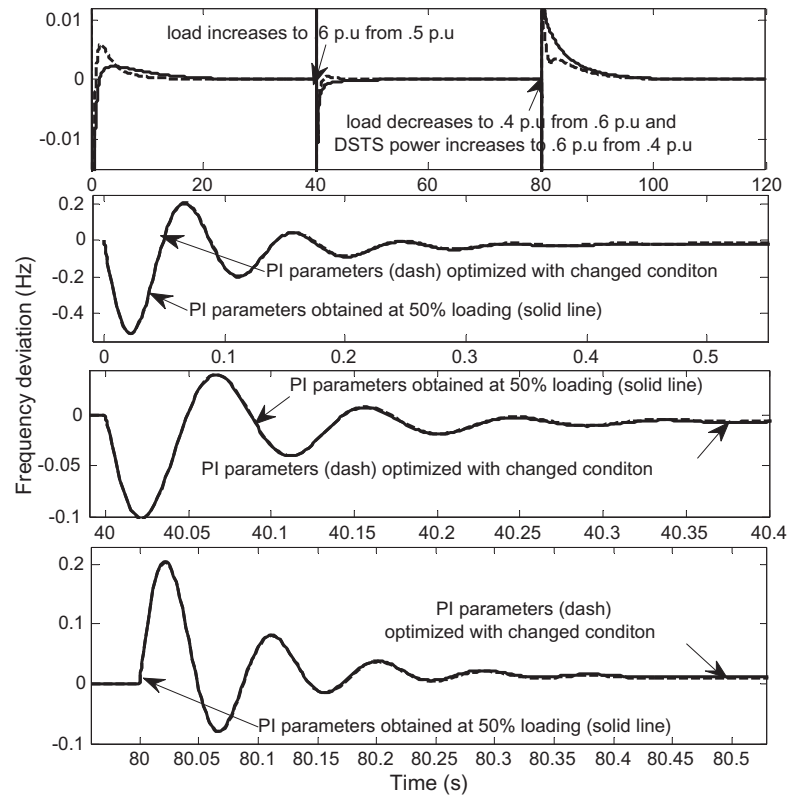


Fig. 7b. Frequency deviation in case of GA optimized PI controller.

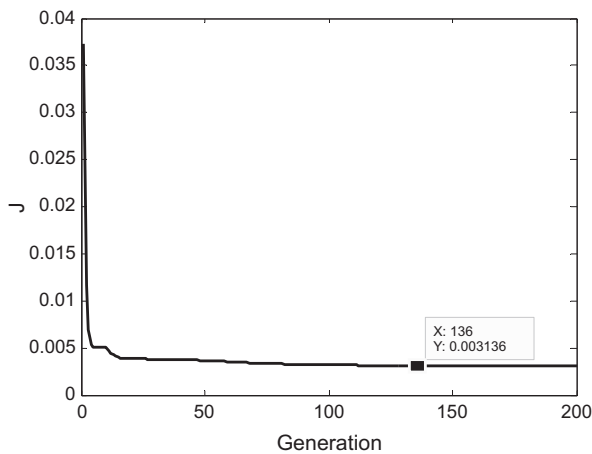


Fig. 7c. Plot of objective function value versus generation for the model with GA optimized PID controller.

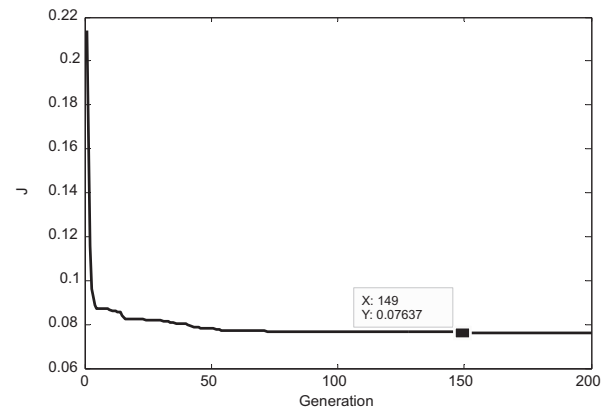


Fig. 7d. Plot of objective function value versus generation for the model with GA optimized PI controller.

In this case, load demand is constant; 50% (.5 p.u) of the nominal value. In order to investigate the system response due to step change in input power, at $t = 80$ s dish-Stirling solar thermal power has been increased to 0.6 p.u from its initial value of 0.4 p.u. During $0 < t < 80$ s, (Fig. 6b) power generated by dish-Stirling solar thermal system is less than load demand; thus diesel generator, fuel cell and battery energy storage device provide the additional power required to meet the load demand. At $t = 80$ s, DSTS output power exceeds the load demand. In both the situations mentioned above, power system frequency fluctuates due to mismatch in generation and demand. The controllers (I/PI/PID) employed in hybrid system, automatically adjust the output power of DEG, FC, and BESS and input power of AE (Fig. 6c) to corresponding values such that the

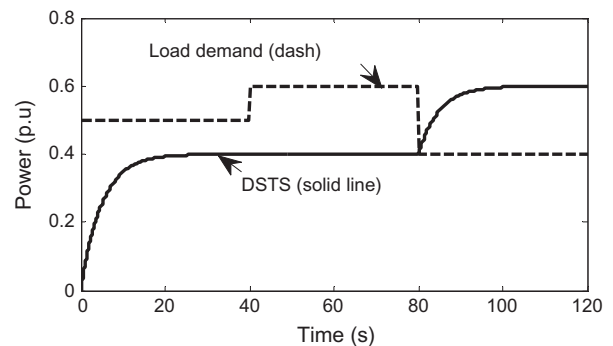


Fig. 7e. Load demand and output power of DSTS.

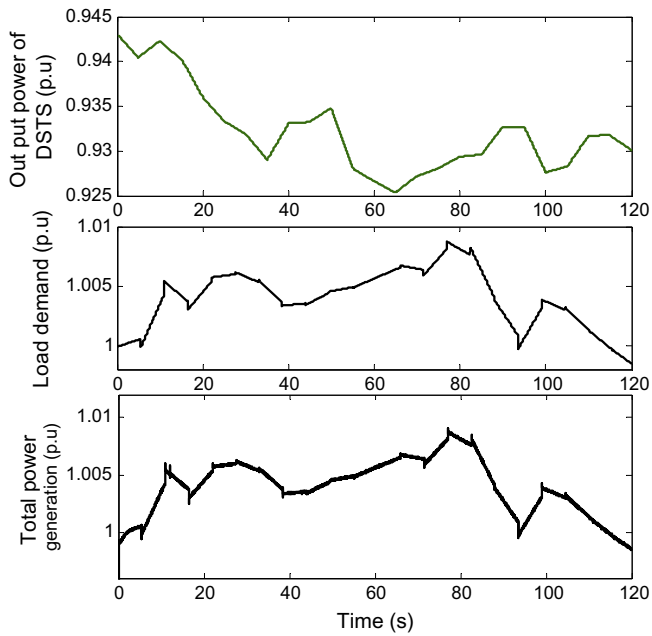


Fig. 8a. Load demand, output power of DSTS and total power generation under randomly varying conditions.

error in matching of supply–demand, and the deviation in frequency are minimum. Fig. 6c shows the input power variation to AE, output power variation of DEG as well. Output power of

variation to BESS, and FC are presented in Fig. 6d. Fig. 6b shows the step changes in dish–Stirling solar thermal power, constant load demand and total power generated. Finally, frequency settles to a steady state value because of action of the controllers. The gain values of the controllers obtained through manually tuned I controllers and its GA counterparts, and GA optimized PI, PID respectively, are presented in Tables 4 and 5. Fig. 6(a) shows the frequency deviation of the hybrid power system. Table 6 presents the maximum frequency deviations (Δf in Hz) of wind–diesel systems for various operating conditions. Investigation reveals that maximum frequency deviation occurs during initial mismatch in generation and load. It may be observed that the GA optimized I controller is better than its manually tuned counterpart in terms of peak transient deviation and settling time. Amongst all the controllers considered for this case, the response of GA optimized PID controller is the best in terms of peak transient deviation and settling time. The plots of objective function value versus generation for I, PI and PID are shown in Fig. 6(e), 6(f) and 6(g) respectively. In all the cases, I represents conventional I controller. The Flowchart for Genetic algorithm is presented in Fig. 5.

Figs. 4a, 4b, 4c and 4d represent the optimization of conventional I controllers employed for AE, FC, DEG and BESS, respectively.

Because of their better performances; GA optimized PI and PID controllers are considered for sensitivity analysis.

Sensitivity analysis: case 2

Sensitivity analysis is carried out to study the robustness of the optimum PI and PID controllers' gains obtained at nominal

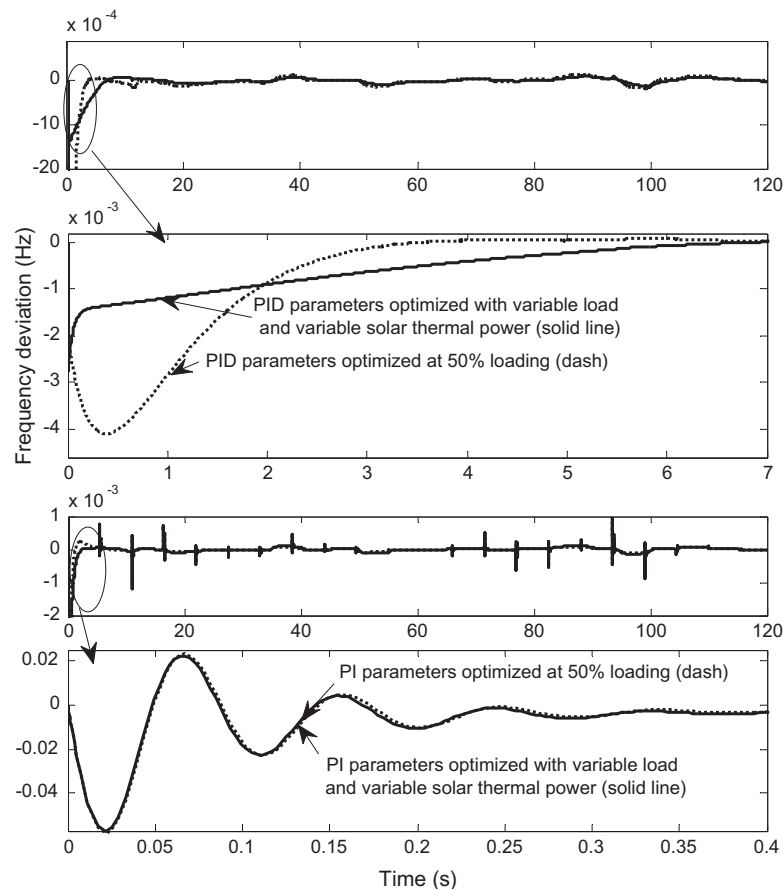


Fig. 8b. Frequency deviation.

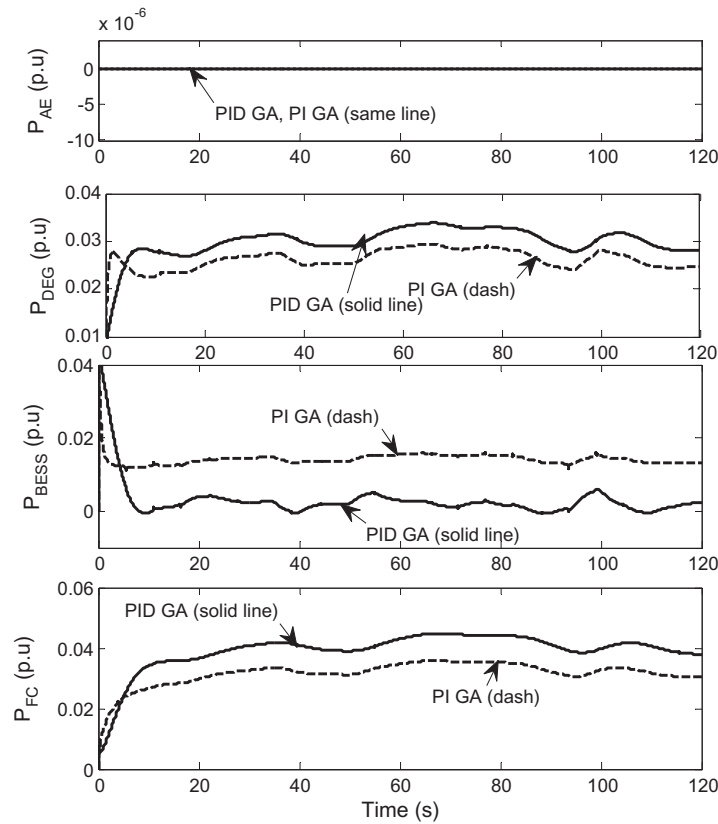


Fig. 8c. Output power of DEG, BESS, FC and input power of AE.

conditions to wide changes in the system condition like, loading condition by $\pm 20\%$ from its nominal loading of 50%. Fig. 7e provides the variations in load demand. At $t = 40$ s, load demand increases by 20% of its nominal loading of 50% and at $t = 80$ s, it reduces to .4 p.u (80% of its nominal loading of 50%). Under this changed conditions, PI and PID parameters are optimized and presented in Table 5. Corresponding responses of frequency deviation are compared with that of obtained at 50% loading. Figs. 7a and 7b show the dynamic responses of frequency deviation for GA optimized PID and PI controller based system, respectively. Their corresponding plots of objective function value versus generation are presented in Figs. 7c and 7d, respectively. From the different magnified portions of frequency deviation in Figs. 7a and 7b, it is observed that there is negligible difference between the responses obtained with changed loading conditions and nominal loading conditions. Which reveal that the optimum values of PI, PID controller gains obtained at the nominal loading of 50% need not be reset for wide changes in the system loading or size and location of step load perturbations.

Random variation in load as well as output power of DSTS: case 3

In order to examine the effects of practically variable nature of dish-Stirling solar thermal power and load demand on dynamic performance of the hybrid system, randomly variable dish-Stirling solar thermal power, and load model are considered. Variable dish-Stirling solar thermal power is obtained using Eq. (2). Load model used for variable load demand is presented in Fig. 8f. The characteristics of these two quantities are provided in Fig. 8a. In order to eliminate the mismatch between generation and load demand, the output power of the battery energy storage system, diesel generators and the fuel cells are altered because of the action of the controllers. The output powers of these generating units and

input power to the AE are presented in Fig. 8c. Due to variations in load and DSTS power, variations also observed in nature of the output power of the battery energy storage system, diesel generators and the fuel cells. Input power to AE is zero. Because of the action of the controllers, the power outputs of these generating units follow the variation in load demand and accordingly change so that frequency deviation (Fig. 8b) is reduced. The gain values of the controllers obtained through GA technique under varying conditions

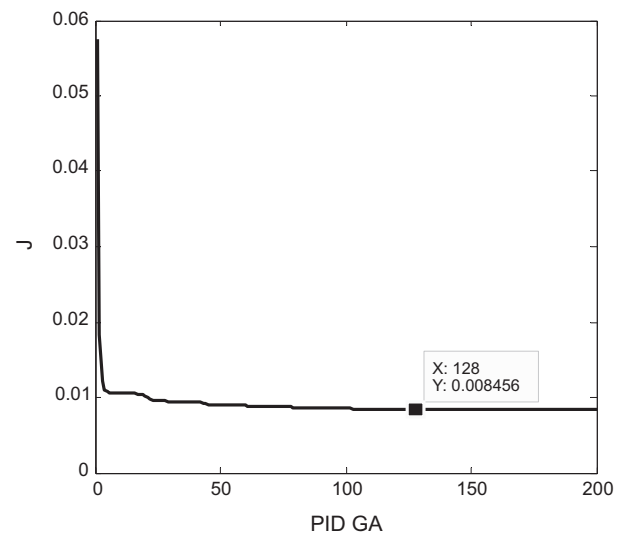


Fig. 8d. Plot of objective function value versus generation for the model with GA optimized PID controller under randomly varying conditions of load demand and randomly varying conditions of power generation from DSTS.

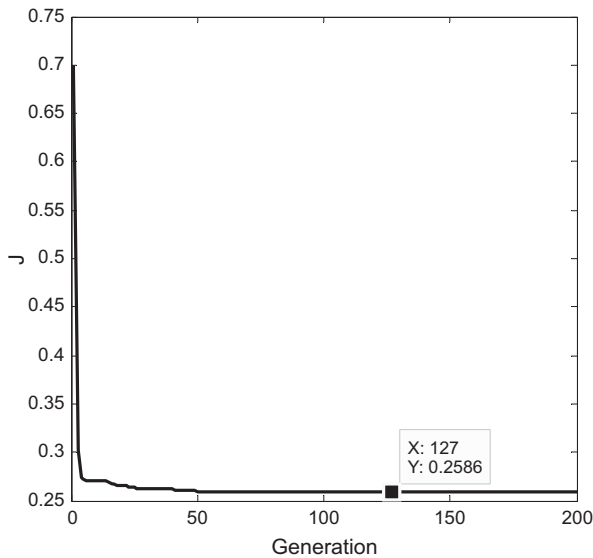


Fig. 8e. Plot of objective function value versus generation of GA optimized PI controller under randomly varying conditions of load demand and randomly varying conditions power generation from DSTS.

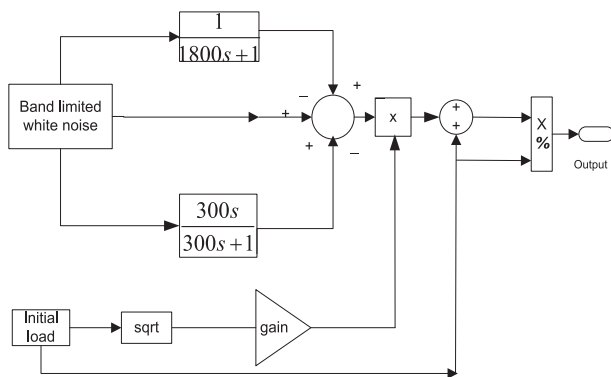


Fig. 8f. Variable load model.

of load and dish-Stirling solar thermal power are presented in Table 5. The performance of PI and PID controllers tuned at 50% nominal loading, are compared with their corresponding counterparts tuned at varying conditions of load, and varying conditions of dish-Stirling solar thermal power (Fig. 8b). Maximum frequency deviations (Δf in Hz) for various operating conditions are presented in Table 6. These responses presented here (Fig. 8b) revealed that the optimum values of PI, PID controller gains obtained at the nominal loading of 50%, need not be reset for wide changes in the system loading or size. The plots of objective function value versus generation for PID and PI are presented in Figs. 8d and 8e respectively.

Conclusion

Small signal analysis of dish-Stirling solar thermal based autonomous hybrid energy system with appropriate modeling has been investigated for the first time. The contribution of this paper includes comparative performance of conventional manually tuned integral controller vis-à-vis GA optimized controllers on this proposed model for maintaining nominal system frequency in the event of variation in loads or variations in solar radiation or both to demonstrate the superior capability of GA in finding better

controller gains. Simulation results revealed that GA-optimized I controller is much better than manually tuned I controller in terms of dynamic responses. Also, amongst the three GA optimized controllers the performance of the PID controller is the best in terms of peak overshoot, oscillations, and settling time. The convergence plots of objective function value versus generation for different controllers on the model confirm the superiority of GA optimized PID Controller over GA optimized I and PI controllers.

Sensitivity analysis is carried out to study the robustness of the gains of PI and PID controllers optimized at nominal conditions to wide changes in the system loading condition by $\pm 20\%$ from its nominal loading of 50%. Investigation of dynamic responses reveal that the optimum gain values obtained at the nominal loading condition are quite robust and need not be reset for wide changes in system loading conditions.

Therefore, the proposed GA optimized PID controller can effectively ensure the real power balance condition despite variations in power generated by DSTS and or variation in load; the power generation from the DEG, FC, and input power to AE as well as the energy storage stored in or released from the BESS. Further research works can be carried out on the performance of other controllers like integral double derivative (IDD), fuzzy based intelligent controllers etc. together with other meta-heuristic optimization algorithms like Cuckoo search, Bat algorithm etc.

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